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This automatic response was expressly deisnged to deliver acceptable water rates even during the abrupt power excursions encountered in emergencies, including collision-avoidance crashback maneuvers. The transient test data indicated unacceptable flameout in the engine during engine deceleration to idle speed. Detailed analyses of the flameouts show that the controller can reduce water flow within two deciseconds of a change in power demand. However, the residence time of water in the manifolds can be about a second for some operating conditions. Several fixes for this problem are described.

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# WATER INJECTION INTO NAVY GAS-TURBINE COMBUSTORS TO REDUCE NO$_X$ EMISSIONS

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## ABSTRACT

Land-based water injection into the combustor of gas turbines is a state-of-the-art technology, which is a low-risk, low-cost option for reduction of gas-turbine emissions. A controller for a water-injected combustor (WIC) system was designed for automatic control of water injection. Steady-state tests of the WIC system in an LM2500 propulsion-engine facility yielded basic engine-interactive data for the WIC's unique automatic software logic. The steady-state tests demonstrated anticipated NO$_X$ reductions in conformity with proposed (but not implemented) California Air Resources Board (CARB) mandates. The controller automatically compensates for the effects of humidity, temperature and engine load.

This automatic response was expressly designed to deliver acceptable water rates even during the abrupt power excursions encountered in emergencies, including collision-avoidance crashback maneuvers. The transient test data indicated unacceptable flameout in the engine during engine deceleration to idle speed. Detailed analyses of the flameouts show that the controller can reduce water flow within two deciseconds of a change in power demand. However, the residence time of water in the manifolds can be about a second for some operating conditions. Several fixes for this problem are described.

## INTRODUCTION

The work described herein was supported by the Strategic Environmental Research and Development Program (SERDP) sponsors, under the Compliance Pillar of the program.

The International Maritime Organization and the Environmental Protection Agency (EPA) have mandated limitations on the emissions of NO$_X$ from new diesel-powered ships passing through territorial waters. Strict enforcement will be imposed by the end of the decade. Gas turbines, which are always cleaner burning, have escaped mandates at this time. However, in Europe, increasingly stricter exhaust emission limits for shipboard turbines near high-pollution ports undergo periodic review. Presently, Dutch and Danish mandates (Gas Turbine World, 1996) on gas-turbine emissions have recently been imposed for the North Sea-platforms. In anticipation of ever stricter mandates, the Navy has been instructed by OPNAVINST 5090.1A to make a good-faith attempt to comply with these limits on emissions in order to avoid costly litigation.

Land-based water injection into the combustor of gas turbines is a state-of-the-art technology, which is a low-risk, low-cost option for reduction of gas-turbine emissions. The retrofit of existing Navy LM2500 engines with the liquid-fuel version of the dry low-NO$_X$ combustors would require a factory replacement of the engine-combustor section. As a result, should the anticipated emissions mandates be invoked, retrofitting LM2500 engines with a water-injected combustor (WIC) system would be less costly.

Table 1 lists the actual emissions (under ideal land-based conditions) from LM2500 engines, the Rolls-Royce RB211, and large gas-burning gas turbines. The actual full throttle NO$_X$ emissions of an LM2500 may exceed 300 ppm. However, with water injection into the combustor, the NO$_X$ emissions can be limited to 42 ppm (General Electric Corp., Undated). This land-based emission limit was the goal of the proposed (not implemented) California Air Resources Board (CARB) mandate, and this WIC program. Such a mandate would affect a Navy inventory of gas turbines including LM2500 engines for propulsion and 501K engines for ship's service power, totaling about 700 units. Should the proposed emission targets be mandated, the Navy would have an available low-cost retrofit technology for compliance therewith.

Substantial quantities of purified water (Pizzino et al., 1991, and Adamson et al., 1996) would be required to suppress the NO$_X$ emissions. Schemes for addressing these requirements will vary in accordance with the ship mission, characterized by transient or permanent operation in the coastal zone. Possible water-management systems for supplying the highly purified water were investigated and described in more detail below.

A controller for a WIC system was designed with both a manual and automatic mode of controlling water injection. Steady-state tests of the WIC system in an LM2500 propulsion-engine facility yielded basic engine-interactive data for the software logic of the WIC controller's unique automatic mode. The steady-state tests demonstrated anticipated NO$_X$ reductions

in conformity with proposed (but not implemented) CARB mandates. The controller automatically adjusts the water rate for the effects of humidity, temperature and engine load.

Tests of the WIC system with an LM2500 engine were conducted at the land-based engineering site of the Naval Surface Warfare Center, Carderock Division (NSWCCD) in Philadelphia. Steady-state operational data reported here show reductions of engine $NO_x$ emissions in both manual and automatic control modes, in compliance with proposed CARB mandates.

Readers of a previous paper (Urbach et al., 1997) will note additional refinements in the software details and new steady-state CO, as well as $NO_x$, emission data for the WIC system.

### WIC-System Water Management for Gas Turbines: Original equipment manufacturers recommend that the maximum level of dissolved impurities for water injection into an LM2500 combustor be less than 2 ppm. Water of this purity may be obtained from distillation plants or multistage reverse osmosis plants (4,5). However, since the production rate of purified water is limited by available shipboard facilities, the method of supplying water to a particular Navy ship class will depend upon the operating mission of the ship.

### A Plan for Fast Traverse of the Coastal Zone:
Damaging fallout from marine airborne pollution may extend up to 150 nautical miles from the site of generation (Corbett and Fischbeck, 1997). However, since California shipping interests proposed a 50-nautical-miles wide maritime pollution zone, this latter width was assumed for the hypothetical discussion below.

For a DDG51-class ship (destroyer), moving through a 50-nautical-mile sea lane off the California coast or through the Dutch and Danish sector of the North Sea (Gas Turbine World, 1996), the time of traverse is estimated to be 3.7 hr. The combined water requirement for two LM2500 engines, two 501K engines, and the ship hotel consumption is 6 long tons per hour (lt/hr), according to Table 2. The results were based upon two engines in crowded sea lanes. However, a reviewer noted that operations in crowded United States waterways require four engines. Computations based upon four engines yield only slight increases in water requirement. A DDG with two 8,000 gallon per day (gpd) distillation plants will produce only 2.5 lt/hr. The total water shortfall will be 13 lt, which may be acquired from 59 lt of water stored in cleansed potable water storage tanks. The ship commander generally prefers to maintain the ship potable water tanks in a full condition for purposes of good seakeeping and readiness. The make-up time needed to replace the 13-lt shortfall in the tanks is 10.4 hr at half-water rations. If the width of the restricted zone is greater than the assumed 50 miles, the above numbers must increase proportionally.

### Proposed Plan for Permanent Operation in the Coastal Zone: Navy ships committed to continuous sustained operation in the coastal zone do not have sufficient capacity in their existing desalination plants to replace their inventories of purified water. It is proposed that such ships would relinquish 40% of their fuel storage spaces for storage of purified water. The water would initially be supplied in port. During underway replenishment of fuel, tankers, which normally supply fuel, would also provide purified water. Should a tactical situation arise changing the nature of their mission, such ships would discharge their inventory of water and take on fuel.

### TECHNICAL APPROACH TO THE WIC SYSTEM
Water injection into a combustor flame reduces $NO_x$ emissions arising from the Zeldovich mechanism by lowering the flame temperature. The water-fuel ratio required to reduce emission of $NO_x$ to 42 ppm has been studied by the original equipment manufacturer (OEM). The General Electric (GE) Company (Undated) has suggested optimum water-fuel ratios varying from about 0.15 near the idle condition to a maximum ratio of 0.88 at full throttle. In addition, GE suggested water-fuel-ratio modifications to account for variations in ambient temperature and humidity. The water-fuel ratio falls as the engine power falls, due to the reduction of the combustor flame temperature. Controlling the water-fuel ratio in accordance with the above schedule would be satisfactory for most land applications. In fact, the suggested water-fuel ratio is often exceeded in order to produce more power, albeit at lower efficiency. However, Navy gas-turbine water consumption rates must be constrained by the limited availability of high-purity water at sea. In addition, the integrated WIC-system and power plant must be dependable during a crashback maneuver. In this maneuver, the gas-turbine decelerates to idle over several seconds, while the propeller blades reverse pitch, followed by rapid gas-turbine acceleration to full power with the propeller in reverse. The crashback maneuver must not subject the ship to an unscheduled loss of power during tactical encounters or in crowded commercial sea lanes.

### Description of the WIC-System Controller for Gas Turbines:
Figure 1 shows the plan and elevation views of the WIC system as developed by the contractor. The overall box volume of the electromechanical unit on its skid (without walk-around area for accessibility) is less than 75.9 $ft^3$. The skid can be oriented on its side, or it may be broken into sections with some increase in volume, to fit within confined spaces. The controlling computer is mounted in a separate standard-size console. Figure 2 is a simplified schematic of the water and fuel piping arrangement of the combined WIC system and LM2500 gas-turbine engine at the land-based engineering site (LBES) in Philadelphia. Among other things, the LBES was designed to simulate the operation of LM2500 engines aboard a DDG51-class ship.

Figure 3 is an electromechanical schematic diagram of the WIC-system controller. On command from the water-pump controller, the WIC system supplies water to the fuel manifold at a 'tee' pipe connection. It restricts water consumption in accordance with the aforementioned requirements.

As shown in Figure 3, a turbine fuel-flow meter upstream of the fuel manifold measures fuel flow, converting the varying frequency output of the meter to an analog current signal, which it transmits to the programmable logic controller (PLC). The PLC computes the required water flow from the fuel flow and the ambient temperature and humidity. Also, the PLC monitors the gas-generator speed to initiate water delivery just above idle speed. The computed output signal from the PLC is fed to a solid-state, variable-frequency, variable-voltage, three-phase driver, which powers a three-phase electric motor. The motor drives a constant-displacement, five-piston diaphragm pump, which pumps water to the fuel manifold in direct

proportion to the motor speed. The water flow rate is monitored by a turbine flow meter that transmits an analog signal to a comparator in the PLC, which after re-computing a corrected signal transmits it to the three-phase driver.

The city water supply in Figures 2 and 3, purified in a Culligan demineralizer, was connected to the fuel manifold at the 'tee'. The flow velocity in the tee induces sufficient shear to homogenize the fuel and water mixture, which flows into the primary (inner) core and secondary (outer) nozzles of the combustor.

**Humidity and temperature compensation:** As mentioned above, the WIC system compensates for both temperature and humidity deviations from standard conditions in the ambient intake airflow. Figure 4 shows the graphical form of the algorithm employed in the software to correct the water-fuel ratios for temperature deviation from 59° F. The graphical form of the algorithm compensating for deviations from 60% relative humidity is shown in Figure 5. Thus, water needs appear to vary inversely with humidity and directly as the temperature.

**The rampdown software algorithms used in the PLC:**
The rampdown algorithm, shown in Figure 6, is designed to maintain acceptable water-fuel ratios during all engine throttle-backs and, for the case of a throttle-back to idle, it terminates engine water flow in the shortest possible time. The ramp-rate formulation was determined from observations in several engine tests.

An analogue voltage device provides the PLC with a continuous indication of the throttle position (angle). The rampdown algorithm is activated when the throttle signal falls at a rate exceeding 1.25 Volt/second (V/sec). On activation, the water-pump flow (PF) is recorded, and, on the basis of fuel flow, a decision is made whether to limit the rampdown or let it proceed unconditionally to minimum pump flow. For fuel flows greater than 5000 pounds per hour (lb/hr), execution of rampdown beyond the initial 0.5 seconds is only permitted as long as the fuel flow continues to decrease. When the fuel-flow stabilizes at a rate less than 1750 lb/hr, the pump flow is held constant. However, if fuel flow stabilizes above this threshold, the steady-state water schedule is resumed.

**Chemical Monitoring Systems:** Chemical monitoring of the $NO_x$ emissions of the LM2500 were performed with both a Rosemount CEM and an ENERAC 3000 chemical analytical system. The line delivering engine-effluent gas samples to the chemical monitoring systems was heated to prevent sample adulteration. The built-in computer of the monitoring equipment corrected all data to 15% oxygen.

Deviations from the average of the $NO_x$ readings were about 18% at 19 parts per million corrected (ppmc), but only 8% at 480 ppmc. Fortunately, at the critical 42 ppmc emission level, data agreement was within the reproducibility of the data. Deviations from the average CO data readings of the two instruments were 5% at 160 ppmc CO, and only 2.5% near 1000 ppmc.

**STEADY-STATE BEHAVIOR OF THE WIC SYSTEM**
The reduction of $NO_x$ by the WIC system during the steady-state operations conformed with design expectations. At powers near 22,500 hp, water-fuel ratios approaching 0.88 yielded $NO_x$ emissions around 42 ppmc in both the manual and automatic modes of WIC-system operation. The reductions of $NO_x$-emissions are approximately proportional to the water rate, in conformance with published data (General Electric Corporation, Undated). The steady-state performance of the manual and automatic modes of the WIC system fulfill the original $NO_x$-emissions criteria needed to qualify for engine-transient operation.

Figure 7 illustrates the reduction of $NO_x$ emissions from the test LM2500 engine in the steady-state automatic mode of the WIC system. Data for the manual mode were similar. The $NO_x$ emissions at or near full throttle may exceed 300 ppmc. With WIC-system injection, the emission levels conform with proposed CARB mandates at 42 ppmc. Lower $NO_x$ emission levels may be obtained simply by increasing the water-fuel ratio, which decreases overall thermodynamic efficiency.

However, the reduction of flame temperature, which decreases $NO_x$ produced by the Zeldovich mechanism, increases CO emission. Figure 8 shows the downside of water injection. Carbon monoxide emissions, highest at engine idle, vary inversely with power. With dry operation, the LM2500 exhibits less than 200 ppmc of CO. With water injection, the CO emission may be increased fivefold. Near full-throttle operation, CO emissions are least because the combustor flame is hottest at these conditions. However, since ecological problems imposed by CO emissions are less significant than those imposed by $NO_x$ emissions, the proposed gas-turbine emission mandates did not cover CO.

**TRANSIENT BEHAVIOR OF THE WIC SYSTEM**
A major impediment to WIC-system transient operation derives from instabilities within the combustor. Flame quenching from excessive heat losses and the blowing downstream of flames from excessive air velocities are some mechanisms of combustor instability. The idle state of the engine is a delicate balance of conditions, wherein the work of compression and viscous dissipations, such as windage and bearing losses, are precisely balanced by the turbine work, while the steady-state flame temperature remains constant.

The dry LM2500, steady-state idle fuel consumption of 800 lbs/hr must provide a minimum margin of flame stability during fluctuations of ambient temperature and humidity. However, to compensate for water injection, upward adjustment of this idle fuel-consumption rate is appropriate.

Each pound of water injected into a combustor represents a 1000-BTU low-temperature heat sink. In the idle condition, when the flame stability is most brittle, water injection represents a massive quenching heat sink that the combustor flame must survive. Fortunately, from the viewpoint of flame stability, (see Figure 7) the idle-condition flame needs little or no water addition to suppress the Zeldovich production of $NO_x$, which indicates a cool flame temperature.

**Transient Response Hardware:** WIC-system transients were executed by closing the throttle over time intervals from ten seconds to one second. The throttle lever angle is reported directly to the PLC to bypass a 0.2-sec time delay in the WIC-software system. During the most rapid transients, water flow must decrease fast enough to avoid flame-quenching at idle, where the flame stability is least. The PLC, the driver, the motor and the pump can react to transients within 0.2 sec, a response time that is normally adequate for slower decelerations.

However, as will be demonstrated, water mixed with the fuel and therefore, resident in the fuel manifold prior to termination of water flow may quench the flame during the faster decelerations.

**Detection of Flameout:** Rosemount flame detectors were inserted into the existing boroscope observation ports of the combustor to sense flameout during transient-mode operation of the WIC system. Two radiation sensors were placed at opposite sides to increase the flame-detector reliability. The detector delivers a positive flameout signal when one of the sensors detects less than the threshold radiation for half a second.

**Experimental Results:** As stated above, flameout may be attributed in large part to water still resident in the homogenized water-fuel mixture of the fuel manifold after stopping water flow. Until that water is completely displaced by pure fuel, the combustor flame is subject to flameout near the idle condition.

The idle fuel flow is designed to accommodate normal fluctuations in the ambient temperature, humidity and pumping rates. Flame stability near the idle condition is generally improved with increments of fuel flow. Unfortunately, the test data show that the idle fuel flow was on the lean side of the stable-flame condition, which is economic and safe practice in the absence of water injection. The data indicate that, in normal dry operation, fuel flow falls below the steady-state idle fuel rate of 800 lb/hr for about 10 seconds. This low fuel-flow rate should not jeopardize flame stability in the absence of water injection. However, with water injection, the probability of flameout is highly magnified. Therefore, the data suggest that for water injection, the present idle fuel-flow rate, at 800 lbs/hr, is too low and should be revised upward. When the flame detectors sensed flameout during the WIC-system tests, the fuel flow was already below levels necessary to sustain flame stability in all cases.

Figure 9 is a time-smoothed graph of events during a three-and-one-half-second deceleration. The dependent variables are gas-generator speed, fuel flow, water flow, the pump command signal, and flame detector signal as a function of time. The data indicate that the fuel flow has fallen below idle level (800 lbs/hr) at 3.5 seconds of elapsed time. Both flame-detectors show a precipitous loss of output signal, demonstrating that flameout has occurred. If the fuel flow were well below the critical 800 lbs/hr, the data would support the argument that an increase of the idle fuel-flow rate is required to avoid flameout during water injection.

**Remediation of the Flameout Problem:** At least two approaches may resolve the flameout problem of the WIC system. One approach utilizes an industrial 'duplex' fuel manifold, developed by GE, which, with an off-engine splitter valve, delivers only water-free fuel to an inner primary set of nozzles. This device prevents water erosion and corrosion under the continuous water-injection demands of industrial applications. The splitter valve ensures that the homogenized mixture of water and fuel goes only to an outer secondary ring of nozzles. The primary nozzles spray only water-free fuel into the flame at all engine powers, which is particularly important at engine light-off when combustor stability is most critical. The splitter valve does not open to initiate delivery of the fuel-water mixture to the secondary nozzles until the engine operates safely above idle conditions. When engine power decreases below a fixed level of manifold pressure, the splitter valve closes. Thus, the spraying of residual water into the flame, when its stability is a serious concern, is avoided.

Another proposed approach to the flameout problem utilizes the existing non-duplex manifold. Since, in the Navy application, the water injection is limited to coastal- zone operation, erosion and corrosion are not factors. It is assumed that re-ignition of a stable combustor flame may be achieved after 4 sec without a hazardous downstream accumulation of unburned fuel. At 800 lbs/hr, (see Figure 9) the fuel accumulation over a period of 4 sec after flameout is less than about 1.0 lb. The WIC system may be programmed to sense a rapid fall of the throttle lever angle, at which point the igniters are continuously energized, at least until the flame-detector signal registers positive for a minimum number of seconds. Although the residual water may quench the flame, the water concentration in the manifold vanishes about a second after water pumping has terminated. With the combustor still hot, and with pure fuel flow boosted to an idle rate above 800 lbs/hr, re-ignition should follow its normal course, thus ensuring safe recovery from chance flameouts. The continuous operation of igniters is described in reference (Pratt and Whitney Co., 1977, 1985). (This second approach may be used with the duplex manifold described above.)

A flameout scenario, similar to that of the last paragraph, has been the subject of an intensive cooperative investigation by Boeing, GE, SNECMA, CFM International, and the Aerospace Industry Association. They have studied the flameout of aircraft engines during landing operations in inclement icy weather. Volk (1992) describes incidents of multiple engine flameout in aircraft landings during heavy hail and rain. These events are associated with operation at idle conditions, which condition is employed to slow the aircraft on approach to the landing strip. Hail is the most dangerous form of water, since hail is more likely to survive passage through the compressor and enter the combustor. To avoid the flameout, "increasing the engine power substantially improves engine tolerance to rain and hail ingestion (Volk, 1992)." Clearly, this practice increases the ratio of fuel to ingested water.

In essence, ensuring a higher idle fuel flow following rapid deceleration parallels the recommendations listed by Volk (1992) and adopted by the Aerospace Industry Association.

**Estimation of the Cost of WIC-System Application:**
The cost of installing a WIC system into Navy LM2500 engines will depend upon whether a duplex fuel manifold is included in the retrofit kit. Table 3 shows the alternative WIC-system costs. The authors estimate the cost of integrating the WIC system into existing Navy LM2500 fuel manifolds at about $110 k or about $90 k less than the duplex-manifold package. This cost appears to be significantly less than the cost of dry low-$NO_x$ combustor systems, which would need labor-intensive rebuilding at the factory. Since the initial-acquisition costs appear to be competitive, the WIC system would be applicable to commercial maritime gas turbines.

**Conclusions and Recommendations:** The Navy has tested an $NO_x$-reducing system (the WIC system) for the LM2500 gas turbine engine based upon the injection of water into the combustor. Tests of the steady-state WIC-system performance have shown satisfactory reduction of LM2500-

4

engine $NO_x$ emissions in agreement with proposed (not implemented) CARB mandates.

The WIC system induced flameouts during transient operation because of residual-water quenching of the flame. That water, in the water-fuel mixture of the manifold, may have a finite residence time on the order of a second after water pumping has been terminated.

Modifications have been proposed, which appear to be reasonable means of eliminating the danger of flameouts. The controller would be re-programmed for increased idle fuel flow. Igniter operation would be continuous during fast decelerations, at least until the flame detector provides positive signals for a safe period of time. In addition, another approach would replace the existing manifold with a GE duplex manifold, which delivers a continuous flow of water-free fuel through a set of dedicated nozzles.

If a retrofit package utilizing the WIC system were required for immediate installation, the duplex retrofit kit would be recommended. However, given time for testing the transient behavior of the existing manifold package, modified as suggested above, the authors believe that the low-cost basic retrofit package would be more than adequate. Indeed, the low-cost retrofit kit would be applicable to general commercial shipping.

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Volk, Larry, 1992 "Power Loss in Inclement Weather," Transactions of the FSF 45th IAS.S & IFA 22nd International Conference at Long Beach, CA p.238-247.

**Table 1.** A summary of selected actual gas turbine emissions (ideal land-based conditions) and current mandates.

| ENGINE COMBUSTOR SYSTEM | CURRENT EMISSIONS PPM |
|---|---|
| DLE[a] RB211 (gas) | 25 |
| LM2500 (oil) | 315 |
| LM2500 (oil plus water) | 42 |
| DLE[a] LARGE ENGINES (gas) | 10 |

| SELECTED EMISSION MANDATES | CURRENT MANDATES PPM |
|---|---|
| CONNECTICUT (old engines, oil, gas)[b] | 75,50 |
| CALIFORNIA (new engines, gas)[b] | <10 |
| CALIFORNIA (old engines, oil)[b] | 42 |
| CALIFORNIA COASTAL ZONES[c] | 42 |
| DUTCH AND DANISH NORTH SEA[d] | 33 |

a   DLE represents the dry combustor technology with low emissions
b   Applies only to land-based gas-turbine engines
c   Proposed but not implemented
d   Current maritime mandate for gas turbines on North Sea platforms

**Table 2.** Water management plan for fast traverse of a DDG through the coastal zone.

| | |
|---|---|
| Estimated traverse time | 3.7 hr |
| Engine water requirement* | 3.5 lt/hr |
| Ship hotel water requirement | 2.5 lt/hr |
| Water distillation rate | 2.5 lt/hr |
| Water shortfall rate | 3.5 lt/hr |
| Existing water storage | 59.0 lt |
| Total shortfall | 13.0 lt |
| Make-up time @ half-water ration | 10.4 hr |

\* Datum based on two or four engines at cruise speed

**Table 3.** Cost estimates for alternative WIC systems.

| COST ITEM | USING THE EXISTING SYSTEM $ k | USING THE DUPLEX MANIFOLD $ k |
|---|---|---|
| MANIFOLD | 0 | 80 |
| WIC SYSTEM | 105 | 105 |
| INSTALLATION | 20 | 30 |
| TOTAL $k | 125 | 215 |

**Figure 1.** Plan and elevation views of the WIC-system controller.



PLAN VIEW

ELEVATION
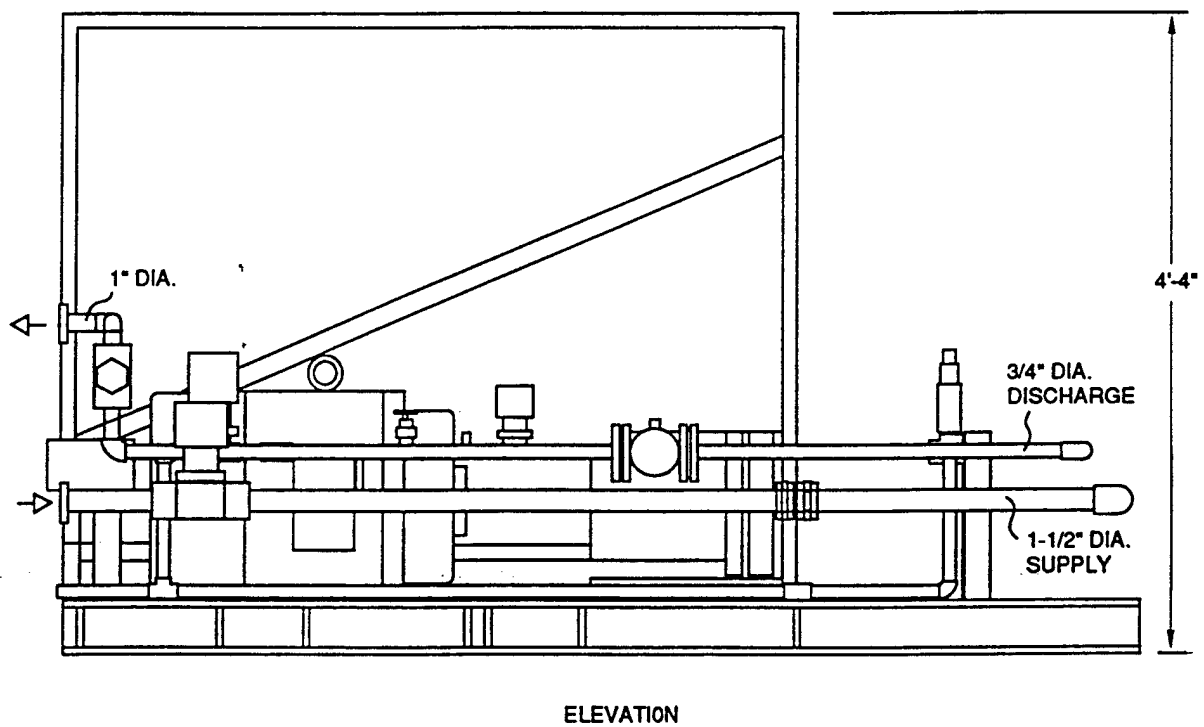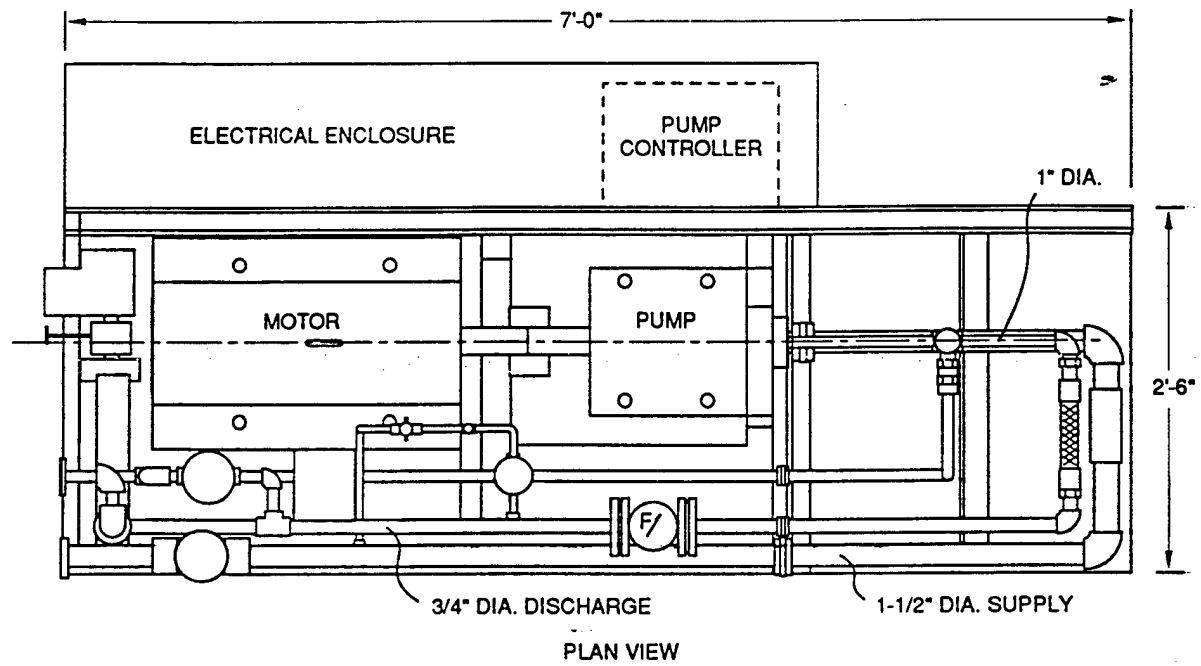
**Figure 2.** Simplified schematic of the WIC-system and fuel-system manifold arrangement for the LM2500 engine.



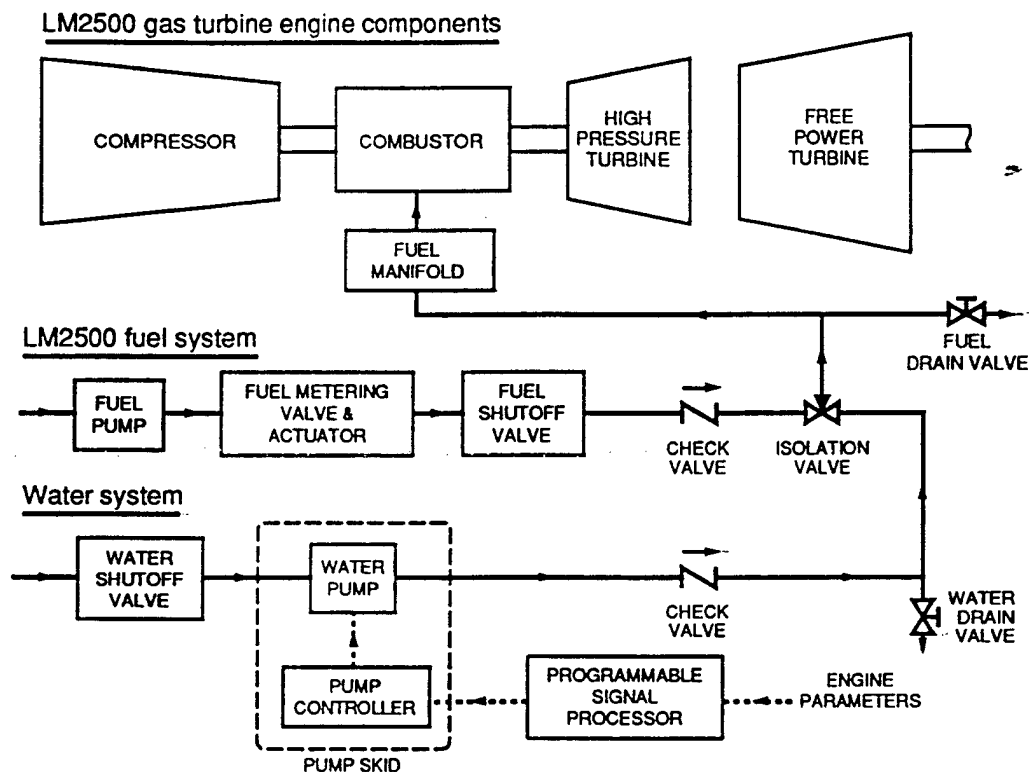LM2500 gas turbine engine components

LM2500 fuel system

Water system

**Figure 3.** Electromechanical configurational details of the WIC-system controller.
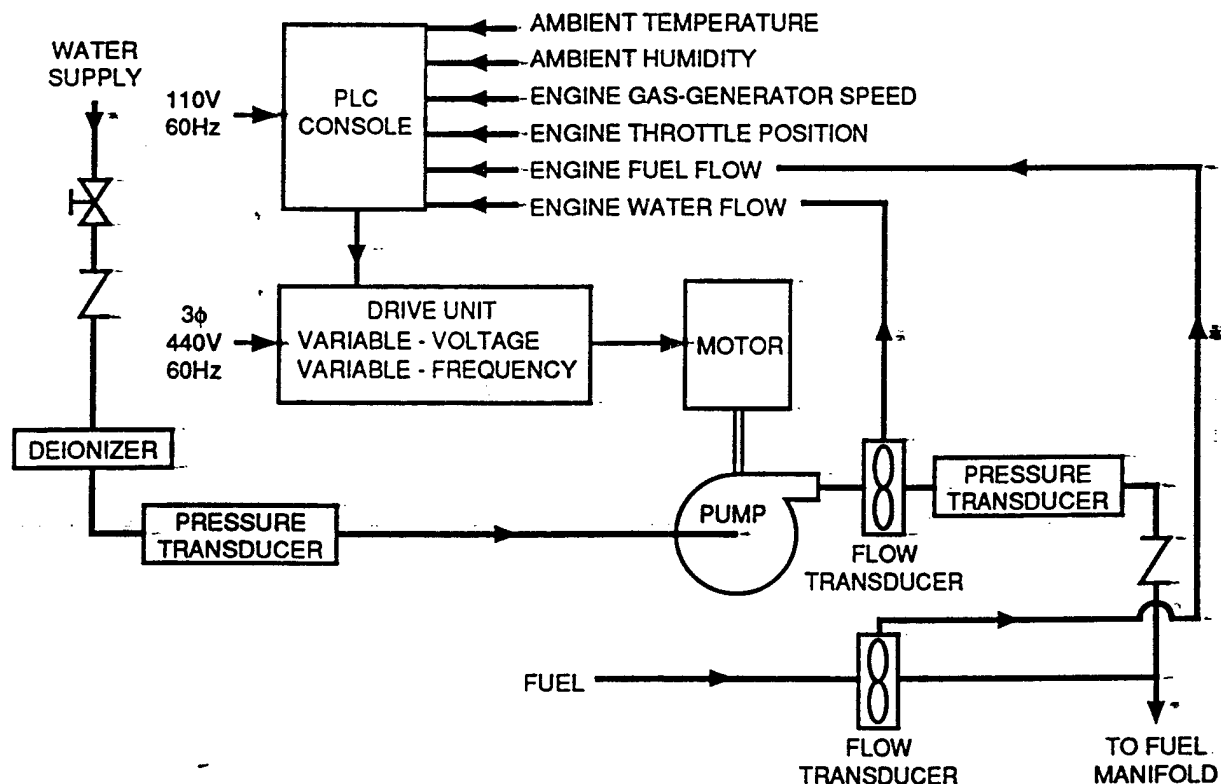
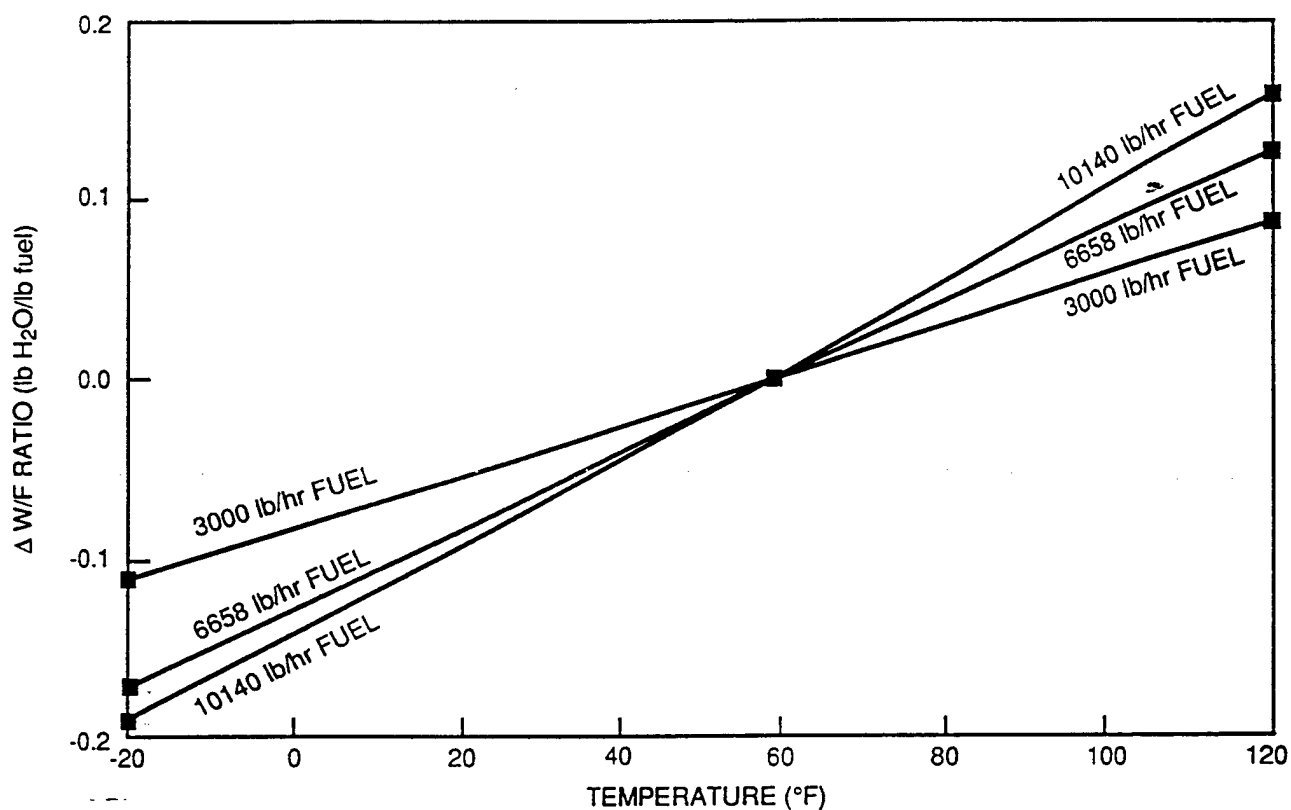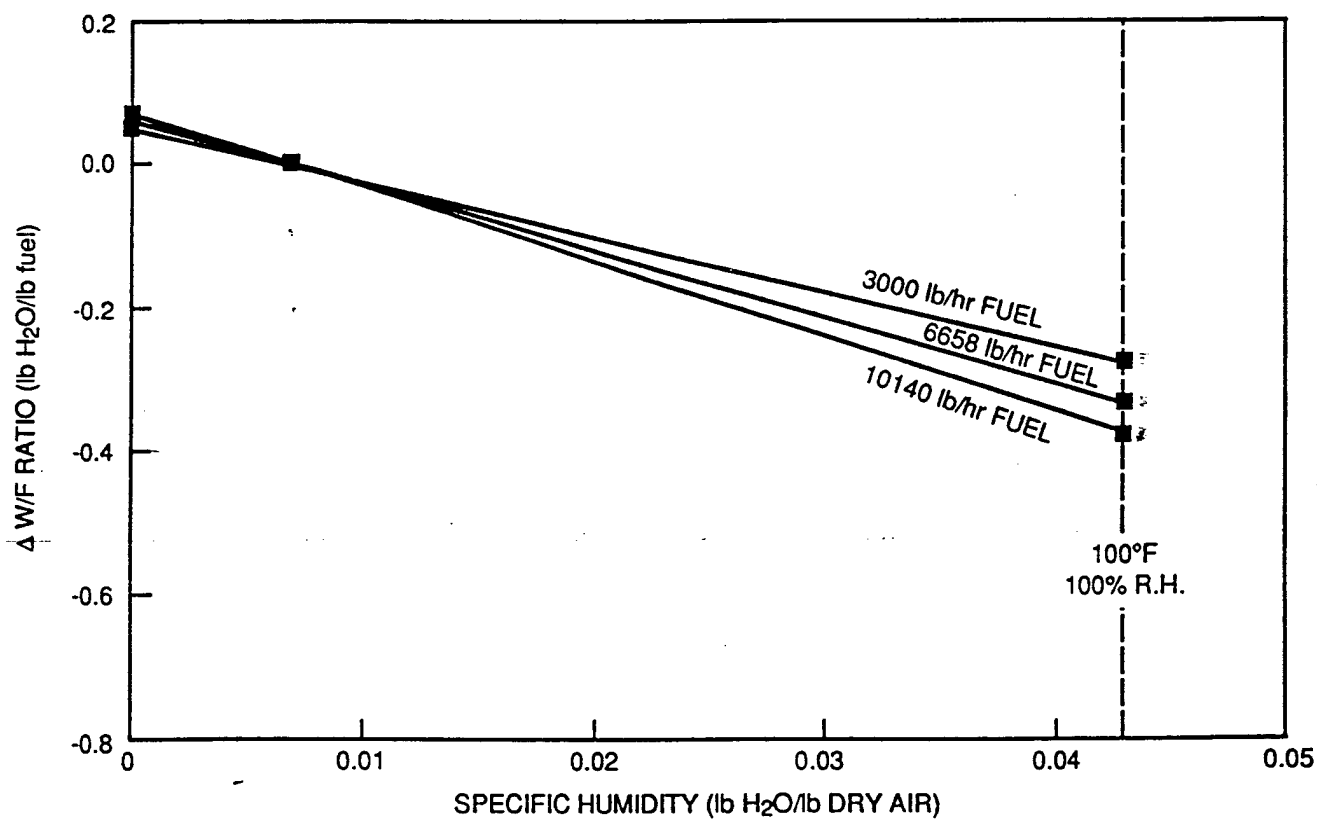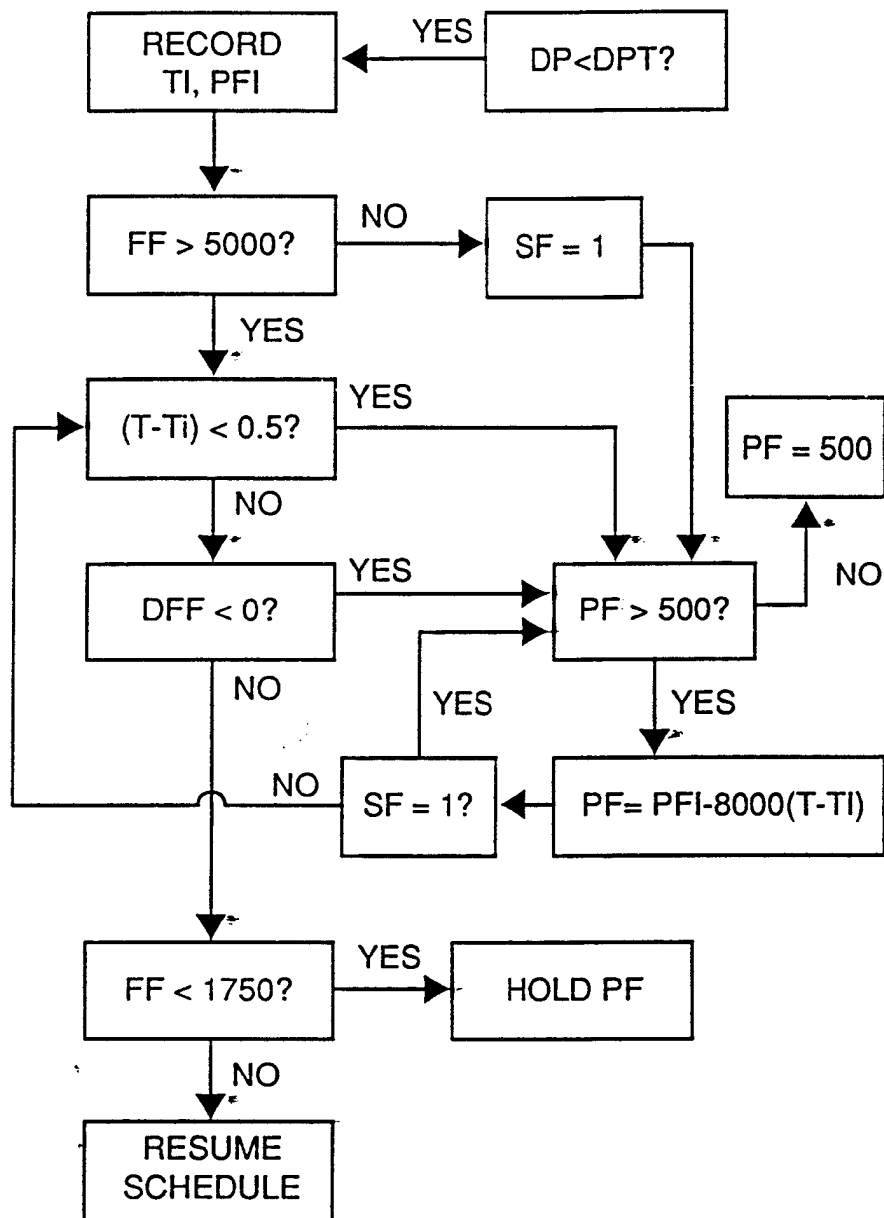**Figure 4.** Graphical form of the computer algorithm for ambient-temperature correction of the water-fuel ratio.



**Figure 5.** Graphical form of the computer algorithm for the ambient-humidity correction of the water-fuel ratio.

**Figure 6.** WIC-system rampdown algorithm for engine deceleration



DP = Time rate of change of throttle (Volts/sec)

DPT = Threshold value of DP = -1.25 V/sec

TI, PFI = Reference values of time (T), in sec, and
water-pump flow (PF), in lb/hr, respectively

FF = Fuel flow (lb/hr)

DFF = Time rate of change of fuel flow

SF = Index value (0 or 1): effects unconditional
rampdown to PF = 500

**Figure 7.** Effect of WIC-system water injection on the emissions of $NO_X$ from an LM2500 gas turbine.
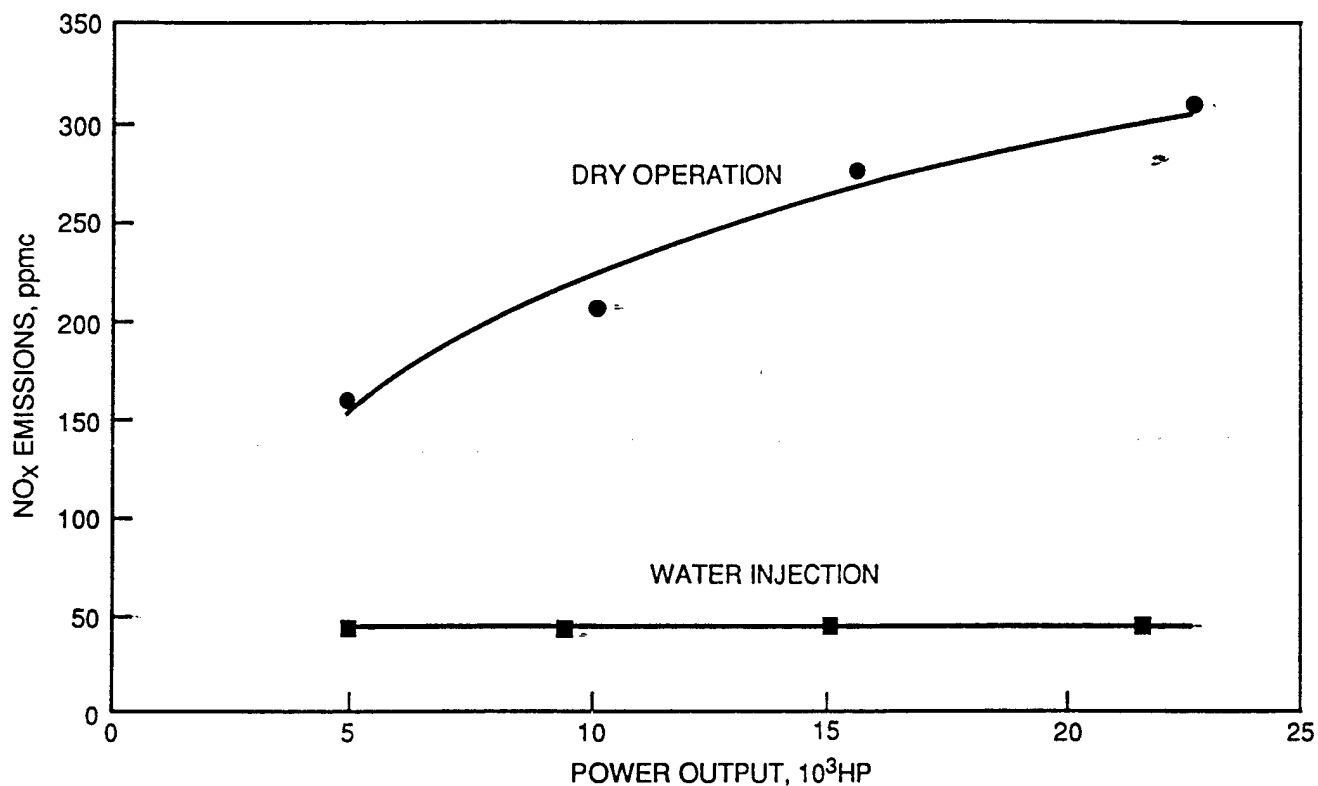


**Figure 8.** Effect of WIC-system water injection on the emissions of CO from an LM2500 gas turbine.
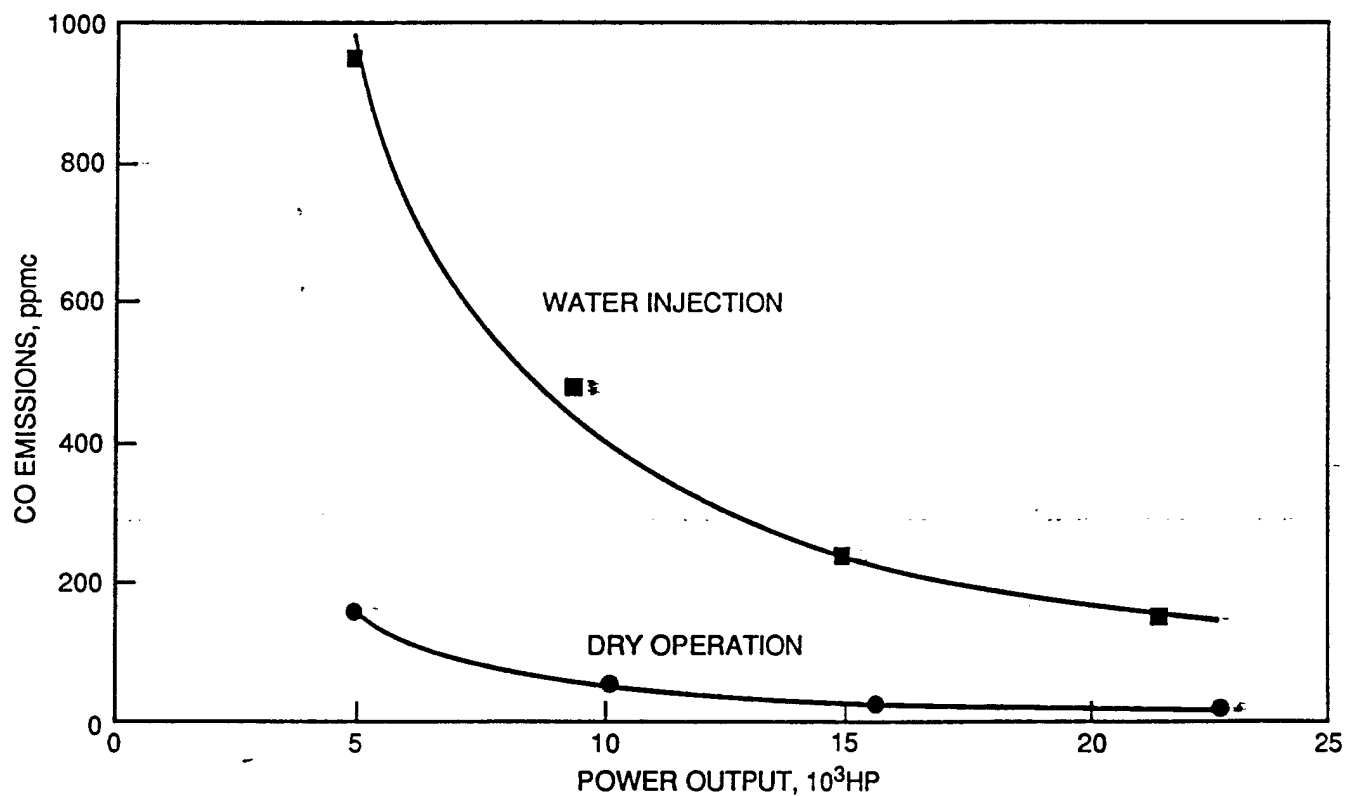
**Figure 9.** Transient behavior of the LM2500 combustor under WIC-system control.